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THE INTERMEDIATE-MASS HIGGS BOSON AND THE FOURTH GENERATION

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ABSTRACT

We study the decay of the intermediate-mass ($m_H < 2M_W$) Higgs boson to fourth-generation leptons (L) at future hadron colliders. The decay $H \rightarrow LL \rightarrow (l\nu_L)(\bar{l}\nu_L)$ yields an observable signal for $120 \text{ GeV} \lesssim m_H < 2M_W$. The cluster transverse mass of the final-state leptons allows a rough estimate of the Higgs-boson mass.

It is well-known that it is difficult to find an intermediate-mass ($m_H < 2M_W$) Higgs boson at future hadron colliders such as the Superconducting Super Collider (SSC) ($\sqrt{s} = 40 \text{ TeV}$) or the CERN Large Hadron Collider (LHC) ($\sqrt{s} = 16 \text{ TeV}$). Such a Higgs boson decays almost exclusively to the heaviest available fermion-antifermion pair. If $m_H > 2m_t$, the top-quark decay mode is dominant; otherwise, the Higgs boson will decay most frequently to bottom quarks. In either case there is an overwhelming background from ordinary QCD production of heavy-quark pairs, which masks the signal.¹

One possible way around this impasse is provided if there are additional heavy particles which couple to the Higgs boson. This may provide alternative decay modes for the intermediate-mass Higgs boson which are not plagued by large backgrounds.

In this paper we explore the ramifications that a fourth generation of quarks and leptons would have on the decay modes of an intermediate-mass Higgs boson. In particular, we examine the scenario in which the dominant decay mode of the Higgs boson is to fourth-generation leptons, $H \rightarrow LL$. This was first suggested as a signal of Higgs-boson production in Ref. 2. It was later explored in Ref. 3, where it was shown that the backgrounds from Drell-Yan and gluon-fusion production of LL were smaller than the signal if an invariant-mass resolution of $\Delta m = 0.05 m_H$ was assumed. However, as was emphasized in that study, this is far from realistic since there are always at least two neutrinos (associated with the L 's) which escape undetected and make an invariant-mass reconstruction impossible. Furthermore, if the heavy leptons decay hadronically, they will appear as jets of particles, so the signal will be two jets plus missing energy, which has an enormous background from ordinary QCD.^{4,5} The signal for one heavy lepton decaying hadronically and the other decaying leptonically is equally hopeless.⁶⁻⁷

In this paper we undertake a more realistic study of the signal and background for Higgs-boson decay to fourth-generation leptons. To avoid QCD backgrounds, we consider

only the leptonic decay of the fourth-generation leptons, which yields a signal of $\ell\bar{\ell}$ ($\ell =$ electron or muon) plus missing energy (due to the loss of four neutrinos), as depicted in Fig. 1. The large amount of information lost to the neutrinos makes a reconstruction of the Higgs-boson mass impossible. Nevertheless, we show that the signal is observable above the background, and that an estimate of the Higgs-boson mass is obtainable from the cluster-transverse-mass distribution.

We also consider the decay $H \rightarrow WW^*$ (the asterisk indicates a virtual particle) where each W boson decays leptonically.⁸⁻¹⁰ The signal is the same as for $H \rightarrow L\bar{L}$, namely $\ell\bar{\ell}$ plus missing energy (this time due to the loss of two neutrinos), so we consider the two decay processes in parallel. This decay mode is substantial only if $H \rightarrow L\bar{L}$ is kinematically forbidden or suppressed.

At present there is no compelling evidence for or against the existence of a fourth generation. Certainly by the time the SSC or LHC is ready to begin taking data we will know whether there is a heavy lepton of mass $m_L \lesssim 60$ GeV from studies of the decay $W^- \rightarrow L\nu_L$ at the CERN $S\bar{p}pS$ and the Fermilab TEVATRON.¹¹ This decay mode already places a lower bound of $m_L > 41$ GeV (Ref. 12) assuming the associated neutrino is stable.¹³ Heavy-lepton masses up to $m_L \approx M_W$ will be explored by the CERN LEP II e^+e^- collider ($\sqrt{s} = 180\text{--}200$ GeV), probably prior to the first run of the SSC or LHC.

We will assume throughout that the fourth generation is sequential, i.e., that it couples to gauge bosons and to the Higgs boson like the three known generations. Furthermore, we will assume that the fourth-generation neutrino is light and stable. These assumptions could be relaxed without necessarily affecting our conclusions, but we will not explore this possibility. We will also assume that the top quark is heavy, $m_t > m_H/2$, such that the decay $H \rightarrow t\bar{t}$ is forbidden. We will discuss the implications of a light top quark at the end.

To study the signal, we need the differential decay rate for the Higgs boson to decay to fourth-generation leptons, followed by leptonic decay of the heavy leptons, as depicted in Fig. 1. Due to the $V-A$ coupling of the W bosons to the final (massless) leptons, there is only one non-zero helicity amplitude; the particles are left-handed, and the antiparticles are right-handed. We used spinor techniques¹⁴ to calculate the amplitude and square it.

The differential decay rate is ($z_W = \sin^2\theta_W$)

$$d\Gamma = \frac{2}{m_H} \left(\frac{4\pi\alpha}{z_W} \right)^5 \left(\frac{m_L}{M_W} \right)^2 m_L^2 |D(W^+)|^2 |D(W^-)|^2 |D(L)|^2 |D(\bar{L})|^2 \\ \times p_1 \cdot p_2 p_2 \cdot p_4 (k \cdot p_2 k \cdot p_3 - \frac{1}{2} k^2 p_2 \cdot p_3) \\ \times \prod_{i=1}^6 \frac{d^3 p_i}{(2\pi)^3 2E_i} \times (2\pi)^4 \delta^4 \left(p_H - \sum_{i=1}^6 p_i \right),$$

where $k = p_L - p_{\bar{L}} = p_1 - p_2 + p_3 - p_4 + p_5 - p_6$, $D(X)$ denotes the denominator of the propagator of the indicated particle, and the momenta are defined in Fig. 1. (The corresponding expression for the decay $H \rightarrow WW^*$ may be found in Ref. 10.) The factor of $(m_L/M_W)^2$ is from the square of the Higgs-boson coupling to the heavy leptons. The other factor of m_L^2 is due to the fact that the $HL\bar{L}$ coupling flips the helicity of the heavy lepton. Since the gauge interactions conserve helicity, a mass term is needed to flip the heavy-lepton helicity back so that the associated neutrinos will have the correct helicities.

As we discussed earlier, the difficulty with observing the intermediate-mass Higgs boson at future hadron colliders lies not in the rate of production, but in the large backgrounds to the decay signature. The standard-model backgrounds to the signal of $\ell\bar{\ell}$ plus missing energy are

$$(a) \quad pp \rightarrow Z^*, \gamma^* \rightarrow \ell\bar{\ell},$$

$$(b) \quad pp \rightarrow Z^*, \gamma^* \rightarrow \tau\bar{\tau} \rightarrow (\ell\nu_\tau)(\bar{\ell}\nu_{\bar{\tau}}),$$

$$(c) \quad pp \rightarrow ZZ \rightarrow (\ell\bar{\ell})(\nu\bar{\nu}),$$

$$(d) \quad pp \rightarrow WW \rightarrow (\ell\nu)(\bar{\ell}\nu),$$

$$(e) \quad pp \rightarrow L\bar{L} \rightarrow (\ell\nu_L)(\bar{\ell}\nu_{\bar{L}}).$$

The first four backgrounds have been discussed elsewhere, so here we comment on them only briefly.^{5,10} The Drell-Yan process, (a), yields no missing energy, and may therefore be eliminated by demanding the presence of missing transverse momentum; we impose $p_T > 20$ GeV. Tau lepton pairs, (b), tend to produce final-state leptons that are either nearly back-to-back in the transverse plane (from Z -boson decay) or of small transverse momentum (from low invariant-mass pairs). These two event configurations may be rejected, respectively, by imposing a cut on the angle in the transverse plane between the final-state leptons, $\Delta\phi(\ell\bar{\ell})$, and on the minimum transverse momentum of each lepton. We impose $\Delta\phi(\ell\bar{\ell}) < 160^\circ$, and $p_T(\ell)$, $p_T(\bar{\ell}) > 20$ GeV. Z -boson pairs, (c), are eliminated by rejecting events in which the invariant mass of the lepton pair is near the Z -boson mass. W -boson pairs, (d), provide the dominant irreducible background.

We must also consider the continuum production of fourth-generation leptons, (e), from both quark-antiquark annihilation and gluon fusion.² It was shown in Ref. 3 that this background is suppressed if a resolution of the $L\bar{L}$ invariant mass of $\Delta m = 0.05 m_H$ is achieved. However, as we have already noted, the invariant mass of the fourth-generation lepton pair cannot be determined, due to the loss of four neutrinos. Therefore, we show in Fig. 2 the transverse momentum spectrum of the final-state lepton at the SSC, for a variety of fourth-generation lepton masses. We have imposed the cuts discussed in the previous paragraph. Also shown is the spectrum from W -boson pairs, process (d) above. We see that the continuum production of fourth-generation leptons is small compared with

the W -boson pair background.

There is also a potentially large background from heavy-quark pair production followed by semileptonic decay of each quark. This is particularly significant in light of the fact that the fourth-generation lepton will surely be accompanied by two heavy quark flavors. However, this background will also contain jets, so in principle it is separable from the $\ell\bar{\ell}$ plus missing energy signal. Whether this is possible in practice is a complicated question which we will not address here.

The intermediate-mass Higgs boson is produced from gluon fusion via virtual heavy-quark loops.¹⁵ We have included a top quark of mass 100 GeV and two fourth-generation quarks of mass 200 GeV in the loop. Fortunately, the cross section is rather insensitive to the actual (unknown) masses of these quarks, as long as $m_Q \gtrsim m_H/2$. Since we are assuming that the Higgs boson cannot decay to top quarks (or to fourth-generation quarks), this inequality is automatically satisfied. Since the amplitude is roughly proportional to the number of heavy quarks in the loop, the addition of a fourth generation of quarks increases the cross section by about an order of magnitude.

In Fig. 3(a) we show the transverse-momentum spectrum of the final-state lepton resulting from the production and decay of a Higgs boson of mass 160 GeV at the SSC, for a variety of fourth-generation lepton masses. We have imposed the cuts described earlier. Both the decays $H \rightarrow L\bar{L}$ and $H \rightarrow WW^*$ are included. The curve labeled $m_L > 80$ GeV is entirely due to the latter process, since the former is kinematically forbidden. As one can see from this figure, the transverse-momentum spectrum is rather insensitive to the mass of the fourth-generation lepton.

Also shown in this figure is the background from W -boson pair production followed by the leptonic decay of each W boson. The signal is about an order of magnitude larger than the background at small transverse momentum. Assuming the standard SSC lumi-

osity of $10^{33}/\text{cm}^2/\text{sec}$, the number of signal events per year is roughly 5×10^4 , which is more than adequate. (Note that we have not summed over the lepton combinations e^+e^- , $e^+\mu^-$, $e^-\mu^+$, and $\mu^+\mu^-$; this will increase the rate fourfold.) We conclude that a Higgs boson of mass 160 GeV will be easily identified if a fourth generation exists, regardless of the fourth-generation lepton mass, if its decay to top quarks is kinematically forbidden.

In Fig. 3(b) we show the results for a Higgs boson of somewhat smaller mass, $m_H = 140$ GeV. Although the raw Higgs-boson production cross section is larger, fewer of the events pass the cuts we are imposing since the final-state leptons are less energetic. Nevertheless, the signal is still appreciably greater than the background for small transverse momentum. The signal is again rather insensitive to the heavy-lepton mass.

Figure 3(c) gives the results for a Higgs boson of even smaller mass, $m_H = 120$ GeV. The decay to fourth-generation leptons is still observable above the W -boson pair background. The decay $H \rightarrow WW^*$, represented by the $m_L > 60$ GeV curve, is suppressed due to the fact that the virtual W boson is rather far off shell; the branching ratio is only about 0.05 (summed over all W -boson final states).⁸ Nevertheless, the signal is comparable to the background, and will therefore double the number of events at low transverse momentum.

If we consider even less massive Higgs bosons, we find that almost none of the events pass the cuts imposed to eliminate the backgrounds. We therefore conclude that an intermediate-mass Higgs boson whose mass exceeds about 120 GeV may be observed via its decay into fourth-generation leptons, or one real and one virtual W boson, regardless of the heavy-lepton mass.

In Fig. 4 we show the cluster-transverse-mass spectrum at the SSC for the same Higgs-boson and fourth-generation lepton masses as in Fig. 3. Also shown is the W -boson pair

background. The cluster transverse mass is defined by¹⁶

$$M_T^2(\ell\bar{\ell}, \not{p}_T) = \left([|\vec{p}_T(\ell) + \vec{p}_T(\bar{\ell})|^2 + M^2(\ell\bar{\ell})]^{1/2} + |\vec{p}_T(\ell) + \vec{p}_T(\bar{\ell}) + \vec{p}_T|^2 \right)$$

where $M(\ell\bar{\ell})$ is the invariant mass of the charged leptons. Due to the loss of neutrinos, a direct measurement of the Higgs-boson mass is impossible. However, the cluster-transverse-mass spectrum has a broad Jacobian peak with an endpoint at m_H , and thus supplies an estimate of the Higgs-boson mass.

The cross sections at the LHC are roughly a factor of four smaller than those at the SSC. Furthermore, the signal-to-background ratio is slightly smaller, due to the fact that the gluon luminosity (which is relevant for the signal) falls off more rapidly than the quark-antiquark luminosity (which supplies the background) for decreasing collision energy. Nevertheless, our conclusions regarding the observability of the fourth-generation leptonic decay of the Higgs boson are about the same for the LHC as for the SSC.

Finally, let us comment on the possibility that $m_t < m_H/2$, i.e., that the Higgs boson may decay to top quarks. The existence of this decay mode will affect our analysis in that it will decrease the branching ratio of the Higgs boson to LL and WW^* . The ratio of the branching ratios to top quarks and fourth-generation leptons is

$$\frac{\text{BR}(H \rightarrow t\bar{t})}{\text{BR}(H \rightarrow L\bar{L})} = 3 \frac{m_t^2 (1 - 4m_t^2/m_H^2)^{3/2}}{m_L^2 (1 - 4m_L^2/m_H^2)^{3/2}},$$

where the factor of three is from color. Thus if m_t is comparable to or less than m_L , the decay $H \rightarrow L\bar{L}$ will be decreased by less than a factor of four. This will still allow the detection of a sufficiently heavy intermediate-mass Higgs boson.

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FIGURE CAPTIONS

Fig. 1. Feynman diagram for the decay of the Higgs boson to fourth-generation leptons and their subsequent decay to light leptons.

Fig. 2. Transverse-momentum spectrum of the final-state lepton, ℓ , from $pp \rightarrow L\bar{L} \rightarrow (\ell\nu_L)(\bar{\ell}\nu_L)$ at the SSC for a variety of fourth-generation lepton masses (in GeV).

Also shown is the spectrum from $pp \rightarrow WW \rightarrow (\ell\nu)(\bar{\ell}\nu)$.

Fig. 3. Transverse-momentum spectrum of the final-state lepton, ℓ , from $pp \rightarrow H \rightarrow L\bar{L} \rightarrow (\ell\nu_L)(\bar{\ell}\nu_L)$ and $pp \rightarrow H \rightarrow WW^* \rightarrow (\ell\nu)(\bar{\ell}\nu)$ at the SSC for a Higgs-boson mass of (a) 160 GeV, (b) 140 GeV, and (c) 120 GeV. The curves are labeled by the mass (in GeV) of the fourth-generation lepton, L .

Fig. 4. The cluster transverse mass distribution from $pp \rightarrow H \rightarrow L\bar{L} \rightarrow (\ell\nu_L)(\bar{\ell}\nu_L)$ and $pp \rightarrow H \rightarrow WW^* \rightarrow (\ell\nu)(\bar{\ell}\nu)$ at the SSC for a Higgs-boson mass of (a) 160 GeV, (b) 140 GeV, and (c) 120 GeV. The curves are labeled by the mass (in GeV) of the fourth-generation lepton, L .

Fig. 2

Fig. 1

Fig. 3

Fig. 4